Evidence of Temporal Variation of Titan Atmospheric Density in 2005-2013

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Overview

- Titan and its Atmosphere
- Cassini Spacecraft and Huygens Probe
- Titan Atmospheric Density Reconstruction
- Observed Temporal Variation of Titan's Density
- Possible Causes of the Temporal Variation
- Summary and Conclusion

Titan and its Atmosphere

- Discovered on 03/25/1655 by Christiaan Huygens
- One of Saturn's 53 named moons
- Second-largest moon in the solar system
  - Equatorial radius of 2,575 km (1,600 miles)
- Titan is of great interest to scientists because it is the only satellite in our Solar system with a substantial, active atmosphere, and complex, Earth-like processes that shape its surface
- Scientific motivation: May shed light on ancient questions such as "Where did we come from?" and, "How did the planets form?"

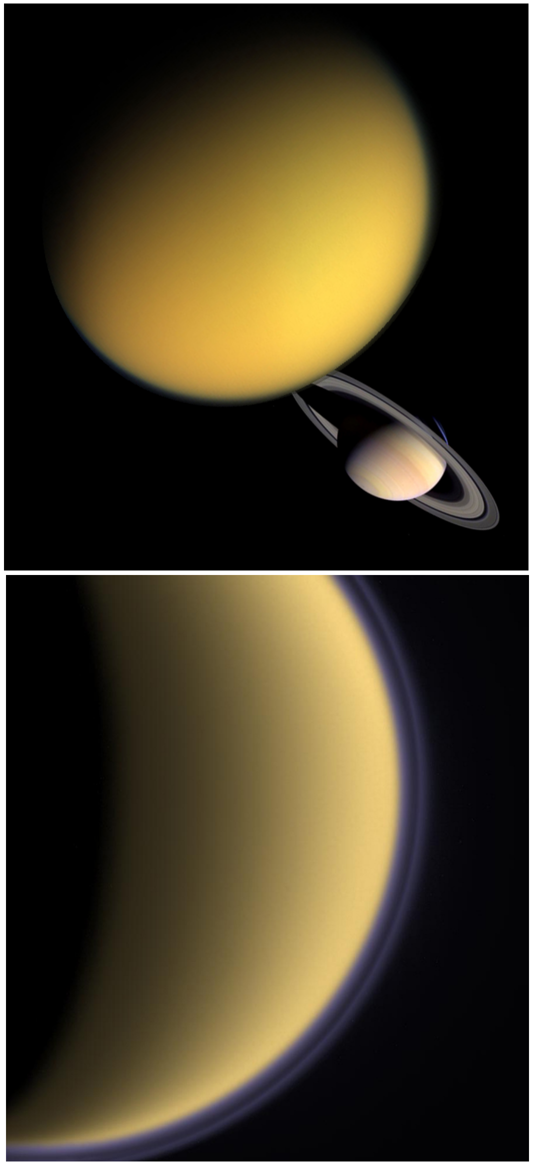
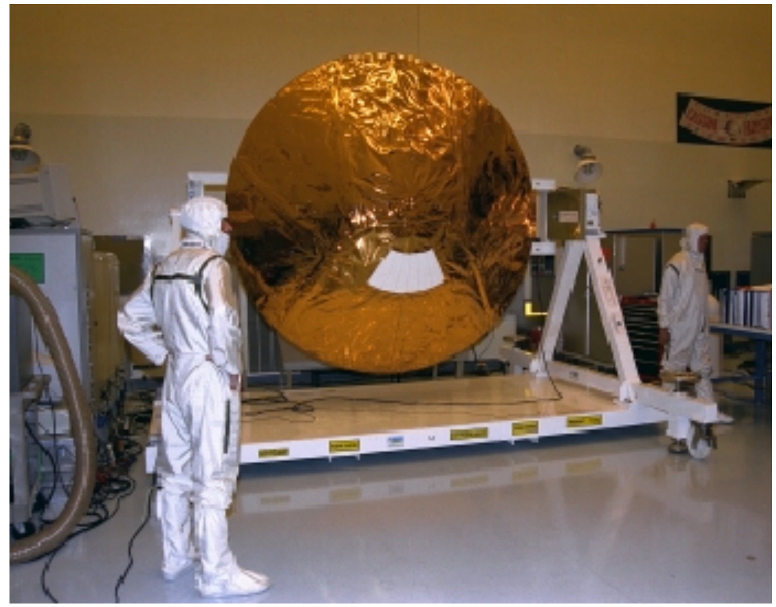


Image credit: NASA/JPL-Caltech

The Cassini Spacecraft and the Huygens probe

- Launched in 1997 & arrived at Saturn in 2004
- ~6.8 m height, ~5800 kg at launch



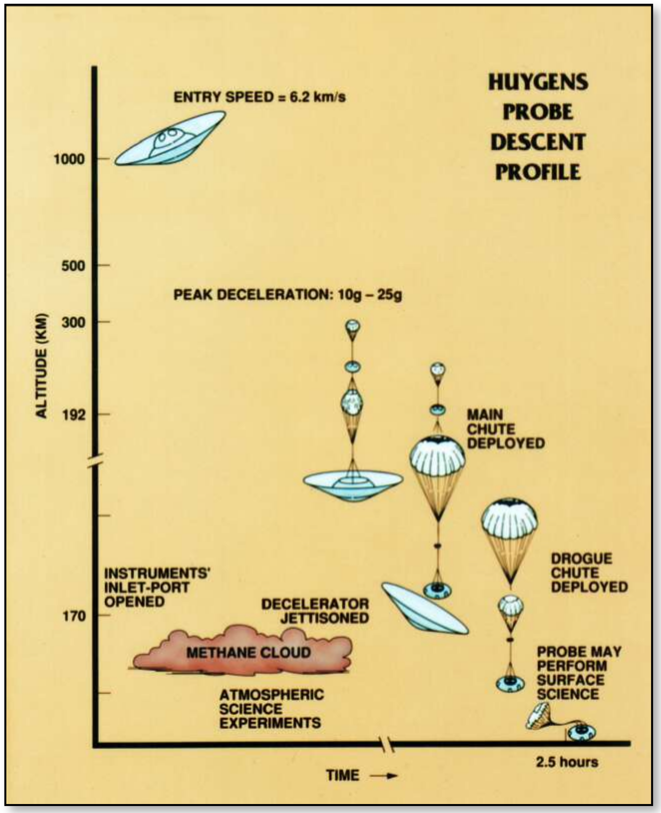
- Provided by European Space Agency (ESA)
- Mounted on –X S/C body axis
- ~2.7 m diameter, ~320 kg

ESA Huygens Probe: Descent Into the Murky Depths

- One instrument carried on Huygens is the Huygens Atmospheric Structure Instrument (HASI). It is a multi-sensor package designed to measure the density, pressure, and temperature of Titan's atmosphere
- HASI sampled and determined Titan's atmospheric density during the Probe's 2.5 hr descent on 01/14/2005

Probe release on Dec 25, 2004

EDL on Titan, Jan 14, 2005



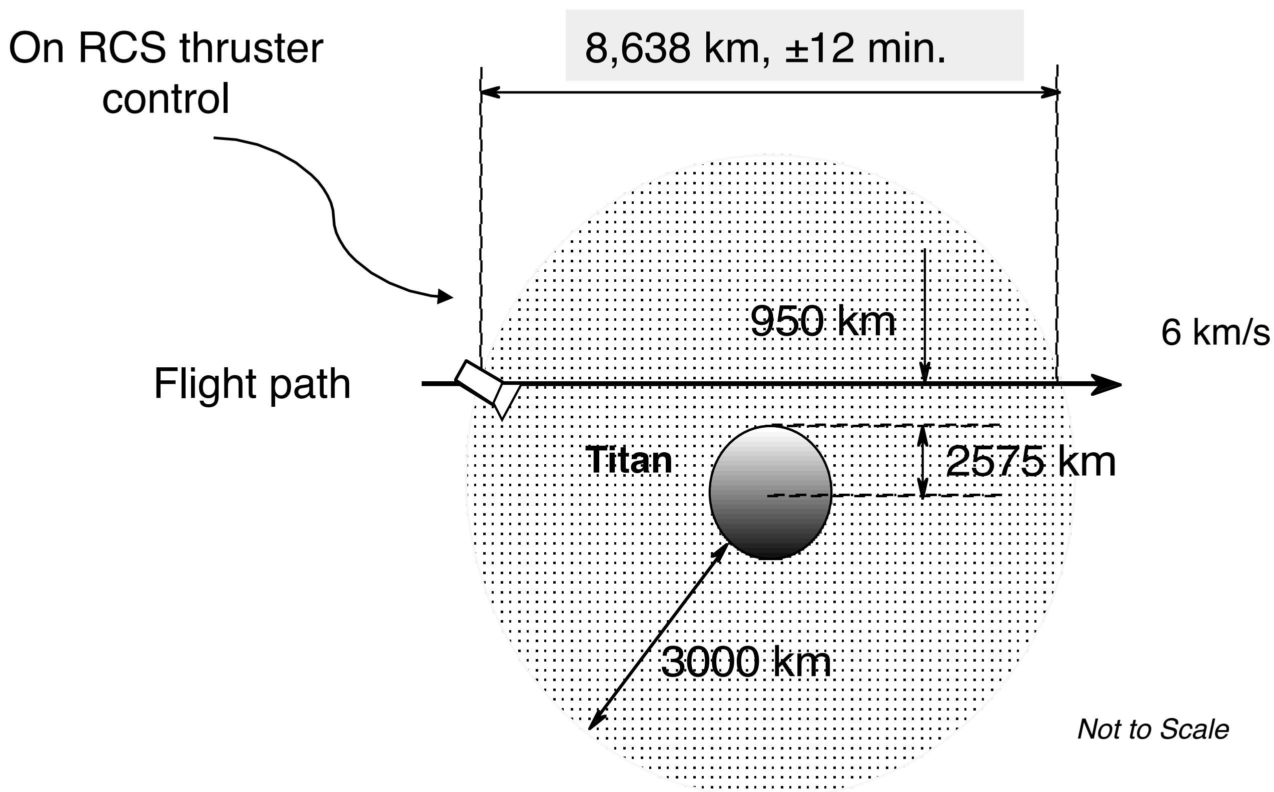
Knowledge of Titan's Atmospherics Density: Why is it important?

- One major science objective of the Cassini mission is an investigation of Titan's atmosphere constituent abundances

- Titan's atmospheric density is of interest not only to planetary scientists but also to mission design, attitude control, and thermal control engineers
  - Unexpectedly high atmospheric density has the potential to tumble the spacecraft during a flyby (controllability issue)
  - Aerodynamic heating of science instruments and/or engineering equipment
  - Hydrazine "cost" of low-altitude Titan flybys
  - Impacts on navigation due to the thruster firing-induced ΔV imparted on S/C
  - Knowledge of Titan's atmospheric density is also needed by ESA Huygens:
    - Huygens probe's heat loading during atmospheric entry (< 600 km)
    - Parachute deployment and landing site prediction (< 400 km)

Low-Altitude Titan Flyby

- 46 low-altitude Titan flybys (with altitudes ≤1,200 km) were executed in 2005-2013
- S/C's attitude is controlled by RCS thrusters
- It is inside the Titan atmosphere only for a short time:
  - For a 950-km Titan flyby with a Titan-relative speed of 6 km/s: 24 min.

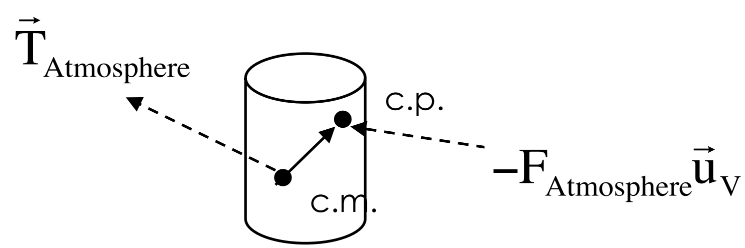


Estimation of Titan's Atmospheric Density

- During low-altitude Titan flyby, thrusters are fired to counter the torque imparted on the spacecraft due to the Titan atmosphere
  - The denser Titan's atmosphere is, the higher are the duty cycles of the thruster firings. Therefore thruster firing telemetry data can be used to estimate the atmospheric torque imparted on the spacecraft
  - Atmospheric torque imparted on the spacecraft is related to Titan's atmospheric density, which is estimated accordingly

$$\vec{T}_{\mathrm{Atmosphere}}(t) = C_d \frac{1}{2}\rho(t)V^2(t)A_{\mathrm{Project}}(t)[\vec{cp}(t) - \vec{cm}] \times \{-\vec{u}_V(t)\}$$

$T_{atmosphere}$	Torque imparted on S/C
C_d	Drag coefficient
V(t)	S/C's Titan-relative velocity
$A_{project}(t)$	Projected area of S/C
P(t)	Titan's atmospheric density
cp(t) - cm	Distance between S/C's c.p. and c.m.
$u_V(t)$	S/C's velocity unit vector



Ground Software for Density Estimation

- A ground software algorithm (that mimics the FSW algorithm) was developed to compute the angular momentum imparted on the S/C due to the external torque:

Reaction wheels are powered off during low-altitude Titan flybys

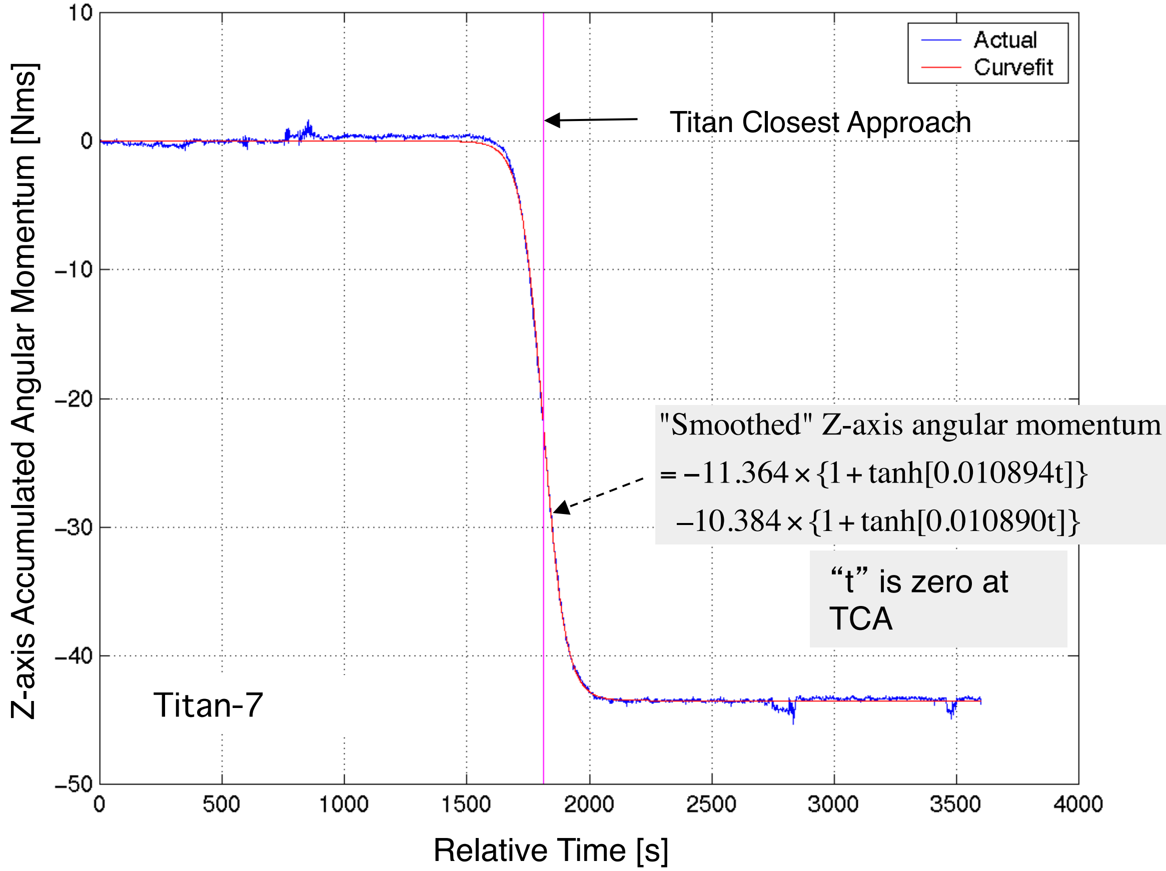
$$\int_0^t \vec{T}_{\text{Atmosphere}}\, d\tau = \int_0^t \left\{ I\dot{\vec{\omega}} + \vec{\omega} \times (I\vec{\omega} + \cancelto{0}{\vec{H}_{\text{RWA}}}) - \vec{T}_{\text{Thruster}} - \cancelto{0}{\vec{T}_{\text{RWA}}} - \cancelto{0^+}{\vec{T}_{\text{ENVIRON}}} \right\} d\tau$$

$$= I[\vec{\omega}(t) - \vec{\omega}(0)] + \int_0^t \vec{\omega} \times I\vec{\omega}\ d\tau \ - \int_0^t \vec{T}_{\text{Thruster}}\ d\tau$$

- All quantities on the right-hand-side of this equation are available from either telemetry or ground estimated values of S/C parameters:
  - Telemetry:
    - $\omega(t)$ are available from the on-board attitude estimator
    - Prime thrusters' on-time are available from the FSW. They are used to estimate the per-axis angular momenta imparted on the S/C using:
      - The thrusters' moment arms (known from pre-launch measurements)
      - Thruster magnitude and tail-off impulse
        - Estimated by ground team based on telemetry and navigation data
  - Parameters:
    - Inertia tensor (I) and S/C's center of mass, etc. are estimated via GSW tools and are also inflight estimated

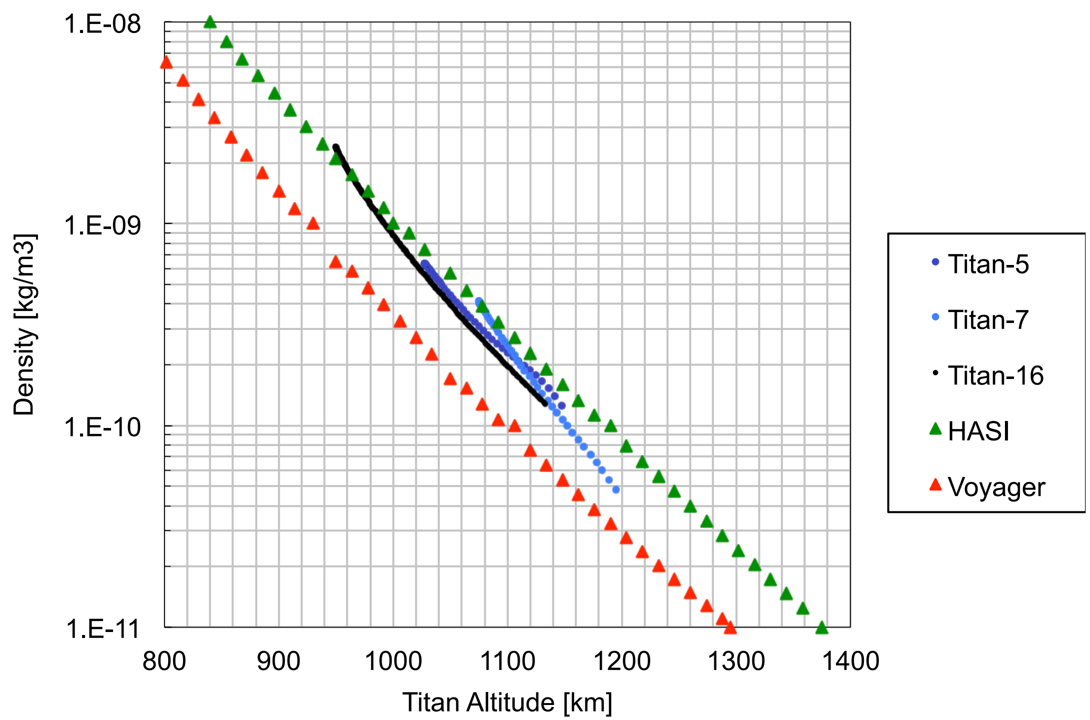
Ground Software for Density Reconstruction (Continued)

- The accumulated per-axis angular momentum is differentiated with respect to time to yield the per-axis atmospheric torque imparted on S/C
  - The "noisy" per-axis angular momenta are first fitted using "analytical" functions. The per-axis torque is estimated accordingly



Comparison AACS Density Estimates to HASI and VOYGER 1 Data

- The HASI (latitude of -10.2˚) results are cross-plotted below with AACS results of three flybys†:
  - Titan-5 (15 April 2005 at a latitude of +74˚)
  - Titan-7 (6 September 2005 at a latitude of -67˚)
  - T-16 (21 July 2006 at a latitude of +85˚)



† Data from these flybys are used because they were executed near the time of the HASI measurements (15 January 2005)
†† Voyager-1 data was obtained in late 1980

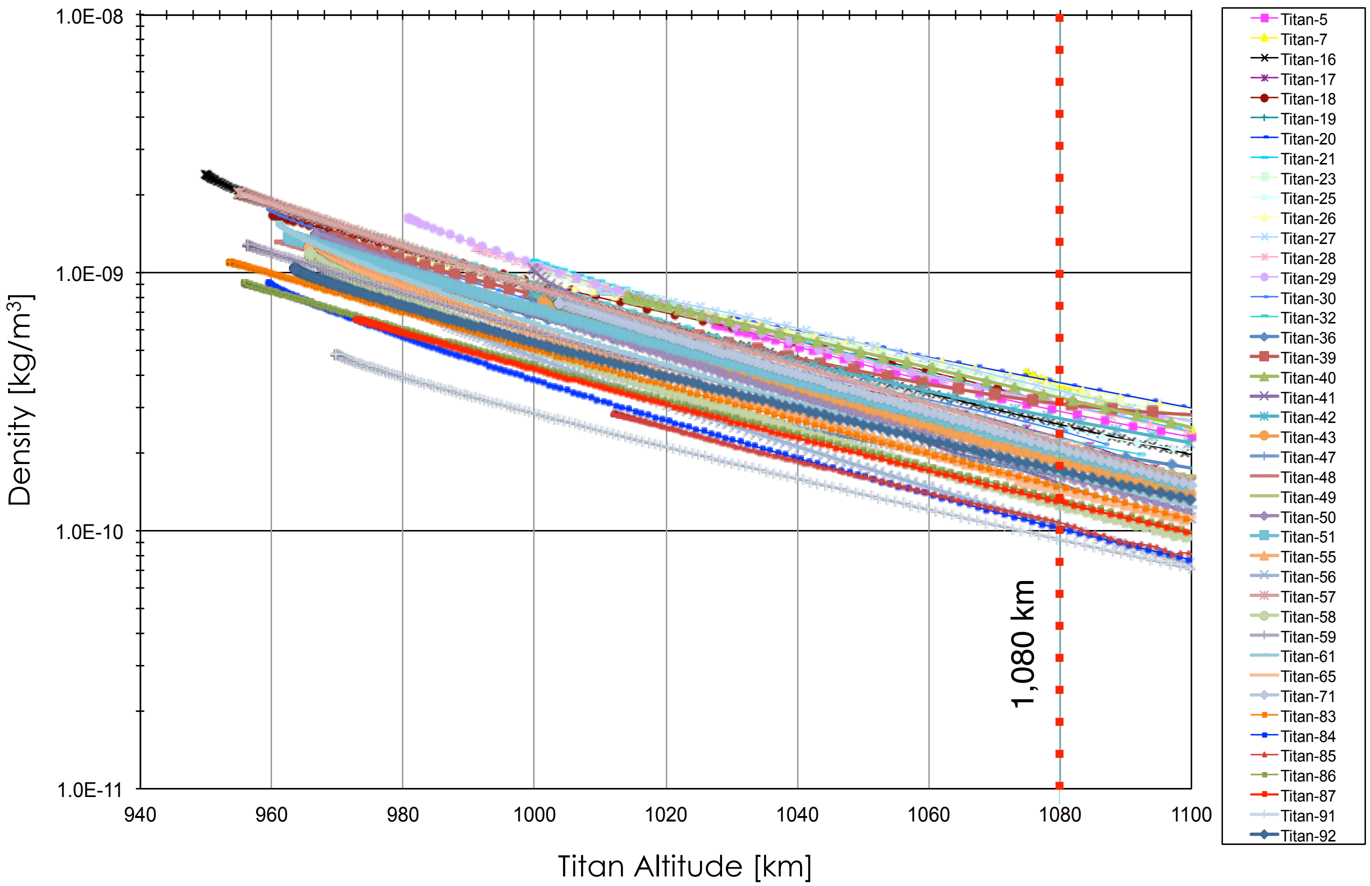
Low-altitude Titan Flybys (2005–13)

Flyby	Date/Time	TCA [km]	TCA Latitude [°]	TCA Velocity [km/s]	Prime Science	Peak Density [10^{-10} kg/m^3]
T5	2005-106T19:12	1027.4	74	6.1	INMS	6.36
T7	2005-250T08:12	1074.8	-67	6.1	RADAR	4.13
T16	2006-203T00:25	949.9	85	6	RADAR	23.3
T17	2006-250T20:17	999.5	23	6	INMS	7.62
T18	2006-266T18:59	959.8	71	6	INMS	16.78
T19	2006-282T17:30	979.7	61	6	RADAR	10.6
T20	2006-298T15:58	1029.5	8	6	ORS	6.7
T21	2006-346T11:42	1000	44	5.9	INMS	11.1
T23	2007-013T08:39	1000.3	31	6	RADAR	10.64
T25	2007-053T03:12	1000.4	31	6.2	RADAR	8.24
T26	2007-069T01:49	980.6	32	6.2	INMS	11.49
T27	2007-085T00:23	1009.9	41	6.2	RSS	8.51
T28	2007-100T22:58	990.9	51	6.2	RADAR	12.61
T29	2007-116T21:33	980.8	59	6.2	RADAR	16.34
T30	2007-132T20:10	959.2	69	6.2	RADAR	17.69
T32	2007-164T17:46	964.9	84	6.2	INMS	16.77
T36	2007-275T04:43	973	-60	6.3	INMS	10.59
T37	2007-323T00:52	999	-22	6.3	INMS	Data lost
T39	2007-354T22:58	969.5	-70	6.3	RADAR	13.67
T40	2008-005T21:30	1014.07	-12	6.3	INMS	8.09
T41	2008-053T17:32	999.7	-34	6.3	RADAR	10.44
T42	2008-085T14:28	999.4	-27	6.3	INMS	8.33
T43	2008-133T10:02	1001.4	17	6.3	RADAR	7.7
T46	2008-308T17:35	1105	-4	6.3	RSS	Data lost
T47	2008-324T15:56	1023.4	-22	6.3	ORS	3.07
T48	2008-340T14:26	960.6	-10	6.3	INMS	13.29
T49	2008-356T13:00	970.6	-44	6.3	RADAR	13.05
T50	2009-038T08:51	966.8	-34	6.3	INMS	14.15
T51	2009-086T04:44	962.6	-31	6.3	INMS	13.81
T55	2009-141T21:27	965.7	-22	6	RADAR	13.3
T56	2009-157T20:00	967.7	-32	6	RADAR	10.81
T57	2009-173T18:33	955.1	-42	6	INMS	20.46
T58	2009-189T17:04	965.8	-52	6	RADAR	11.9
T59	2009-205T15:34	956.2	-62	6	INMS	12.8
T61	2009-237T12:52	960.7	-19	6	RADAR	15.71
T64	2009-362T00:17	951	82	6	INMS	Data lost
T65	2010-012T23:11	1073.9	-82	5.9	INMS	1.52
T70	2010-172T01:27	878	84	6	MAG	39.8
T71	2010-188T00:23	1005	-56	5.9	INMS	7.66
T83	2012-143T01:10	953.5	73	5.9	INMS	10.97
T84	2012-159T00:07	959.6	39	5.9	RADAR	9.09
T85	2012-206T19:47	1012	62	5.9	VIMS	2.85
T86	2012-270T14:35	955.8	62	5.9	INMS	9.12
T87	2012-318T10:22	973	11	5.9	INMS	5.0††
T91	2013-143T17:33	970	46	5.9	RADAR	4.84
T92	2013-191T13:21	963.5	37	5.9	RADAR	10.39

Variations of Titan Atmospheric Density with Altitude (2005-13)

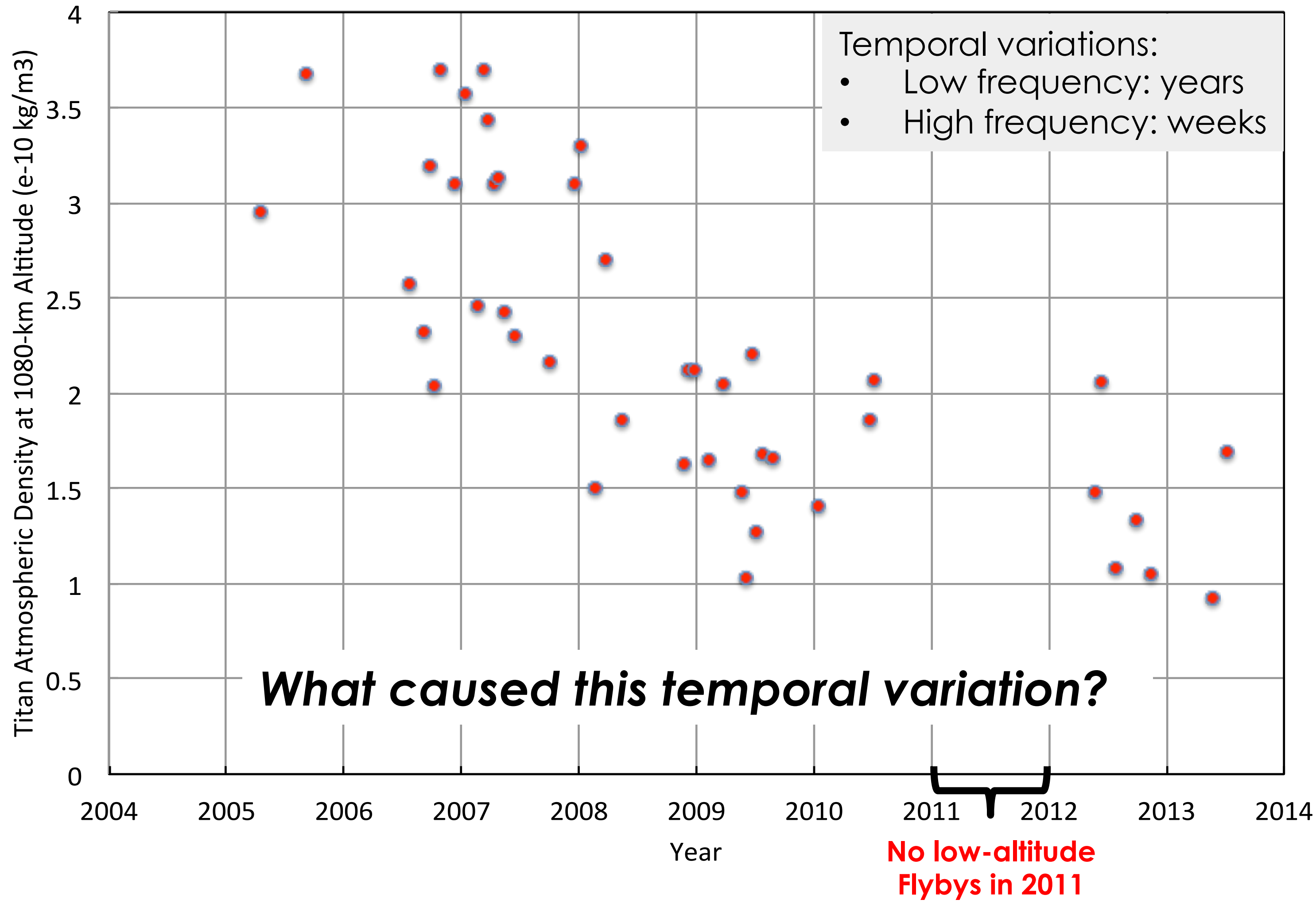
- When density is plotted against altitude, the data sets produce straight lines with negative slopes. Thus, Titan density can be modeled as†:

$$\rho_{\text{Titan}}(\text{h}) = \rho_{\text{o}}\exp(\text{-h/h}_{\text{o}})$$



† Reference density (ρ_o) and scale height (h_o) for low-altitude flybys are given in the paper

Temporal Variation of Titan Atmospheric Density at A Constant Altitude of 1,080 km (in 2005–13)



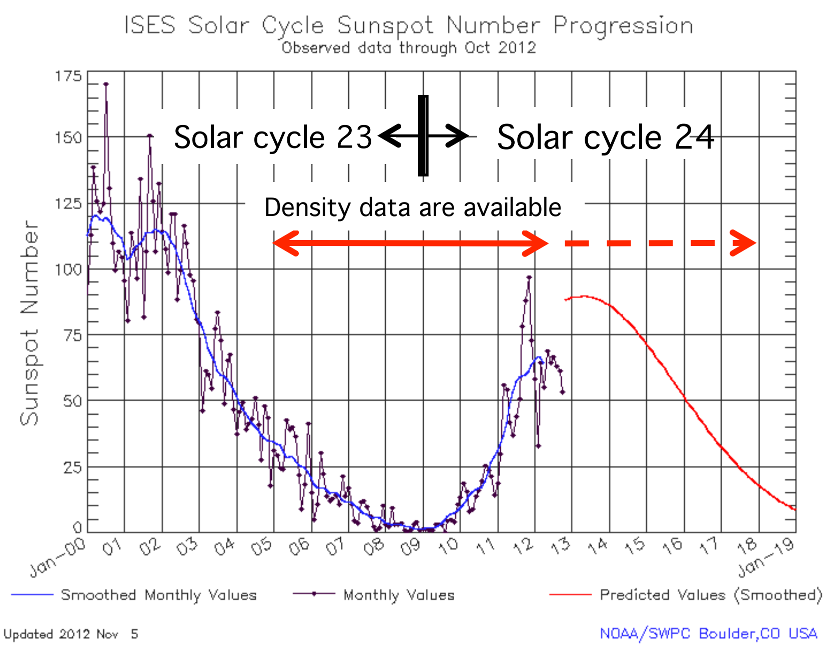
Possible Factors in Changing Titan Atm. Density

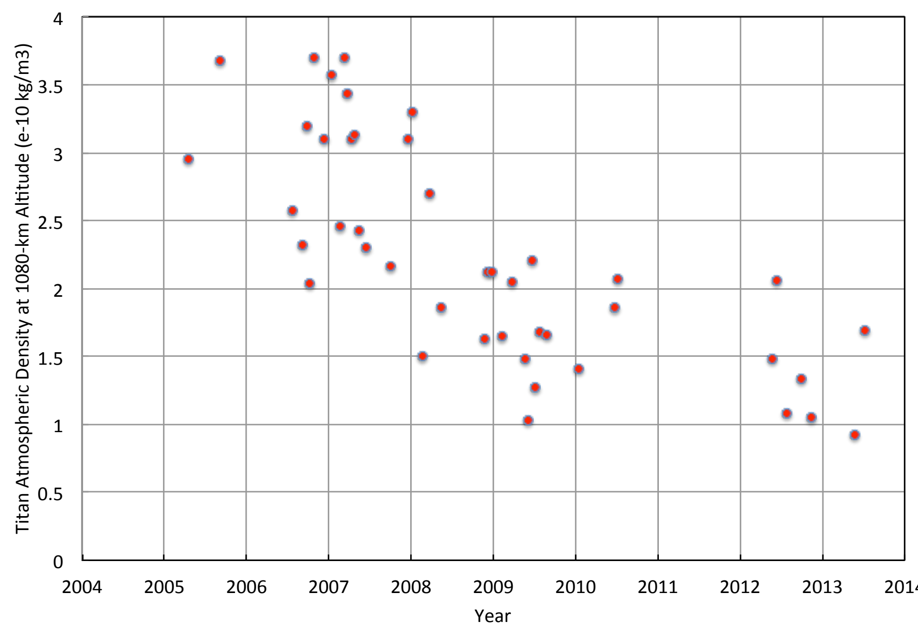
- Beside altitude, what other factors might influence the Titan atmospheric density?

- Conjectures:
  - Solar activity (11-year solar cycle)
  - Flyby TCA (Titan Closest Approach) is in the Sun side vs. shadow
  - Latitude and longitude of flyby TCA
  - Titan atmospheric activities (e.g., storms)
  - Titan surface activities
  - What else?

Possible Influence of Solar Activities

- Solar minimum occurred in December 08–June 09. This is about the same time our estimated Titan atmospheric density was at a local minimal
  - But the atmospheric density did not increase with the observed increased in sunspot number in 2010–2013
    - Solar cycle contributed to the temporal variation of Titan atmospheric density. But there might be other factors

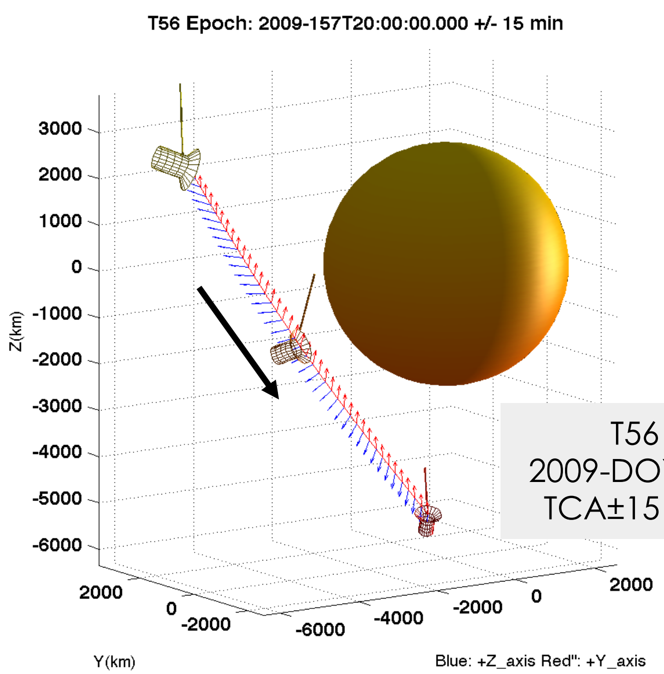


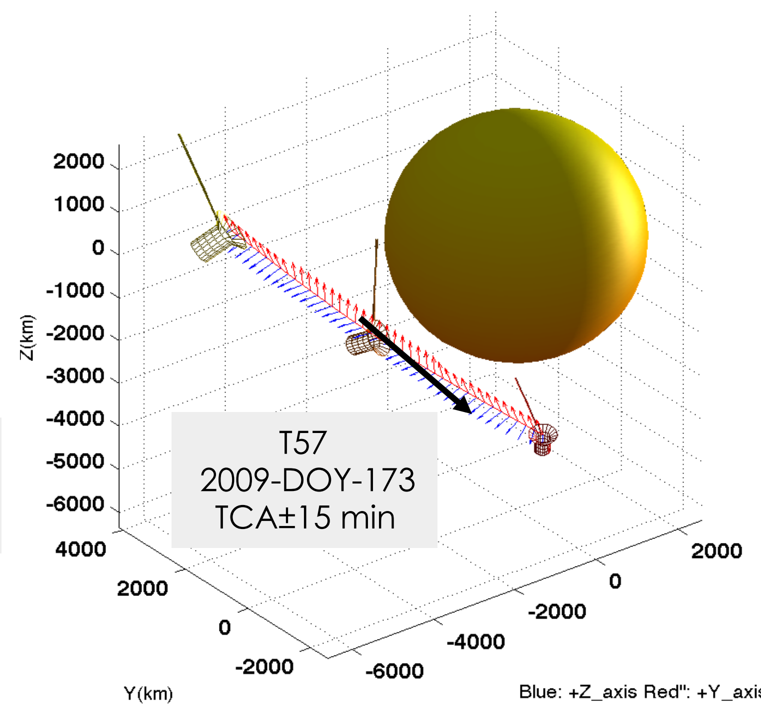


TCA is in the Shadows of Saturn or Titan†

- Titan flybys 56 and 57: Almost the same time, same latitude, same altitude, and both flew by the dark side of Titan
  - But why is there a factor of 2? $\frac{\rho_{\mathrm{TCA}}^{\mathrm{T57}}}{\rho_{\mathrm{TCA}}^{\mathrm{T56}}} \approx 2$

Flyby	TCA Date/Time	TCA [km]	TCA Latitude [°]	Prime Science	Peak Density [e-10 kg/m^3]
T56	2009-157T20:00	967.7	-32	RADAR	10.81
T57	2009-173T18:33	955.1	-42	INMS	20.46

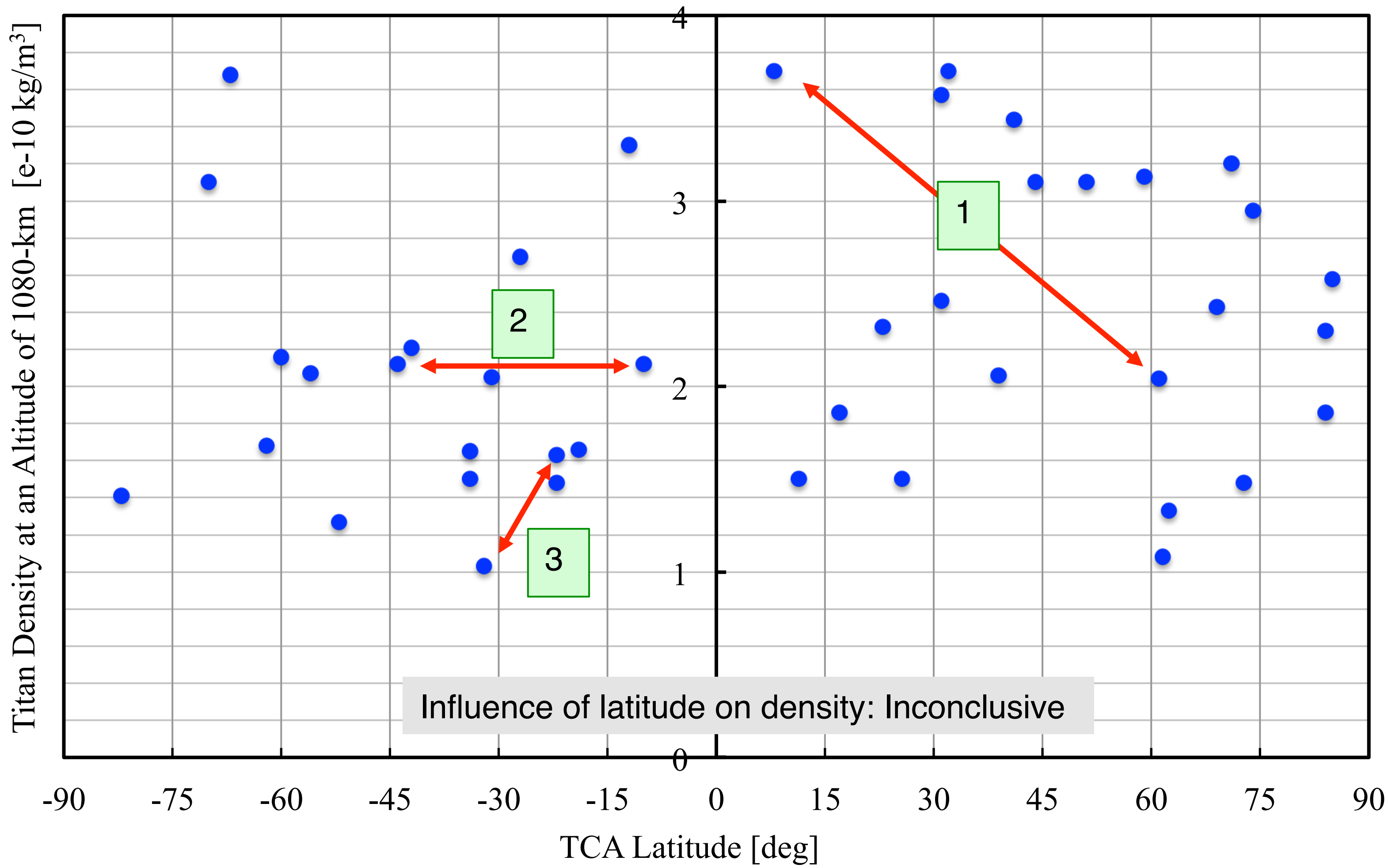




†These "shadow" analyses were performed by Cliff Lee, Cassini SCO AACS team

Variation of Titan Atmospheric Density at 1,080 km with Flyby TCA Latitude (in 2005–13)

Pairs	Flyby	Date/Time	Latitude [°]	1080-km Density [e-10 kg/m^3]
1	T19	2006-282T17:30	61	2.04
	T20	2006-298T15:58	8	3.7
2	T48	2008-340T14:26	-10	2.12
	T49	2008-356T13:00	-44	2.12
3	T55	2009-141T21:27	-22	1.48
	T56	2009-157T20:00	-32	1.03



Future Low-altitude Titan Flybys

- Density Estimates from 18 future (2013–2017) low-altitude Titan flybys will help us better understand the temporal variation of Titan atmospheric density

Flyby	TCA Year/Date	TCA [km]
T93	2013-Jul-26	1,017
T94	2013-Sep-12	1,017
T95	2013-Oct-14	961
T96	2013-Dec-01	1,018
T100	2014-Apr-07	963
T104	2014-Aug-21	964
T105	2014-Sep-22	1,021
T106	2014-Oct-24	1,013
T107	2014-Dec-10	980
T108	2015-Jan-11	970
T113	2015-Sep-28	1,036
T116	2016-Feb-01	1,027
T117	2016-Feb-16	1,018
T118	2016-Apr-04	990
T119	2016-May-06	971
T120	2016-Jun-07	975
T121	2016-Jul-25	976
T126	2017-Apr-22	979

Summary & Conclusions

- Titan is of great interest to planetary scientists
- For low-altitude Titan flybys, mission control engineers need to accurately estimate the Titan atmospheric density for spacecraft safety, especially with decreasing control authority due to decreasing thruster magnitude
- What is causing the observed temporal variation of Titan atmospheric density is unknown at this time
  - It will require synergetic analyses of AACS density data with measurements made by other Cassini science instruments (INMS, CIRS, UVIS, etc.) to determine the possible causes of the temporal density variation
  - Titan atmospheric density will be reconstructed for all future low-altitude Titan flybys. The estimated atmospheric density data will help scientists to better understand the density structure of the Titan atmosphere
- In the mean time, the journey continues …

Titan Explorer
(possible future flagship mission?)

QUESTIONS?

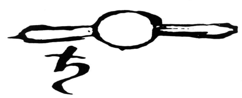
Our Blue Pale Dot taken by Cassini on July 19, 2013

Titan Mare Explorer (TiME)
(possible future discover mission? floating probe exploring Titan lakes!)

Backup Slides

A Timeline of Saturn/Titan Discovery

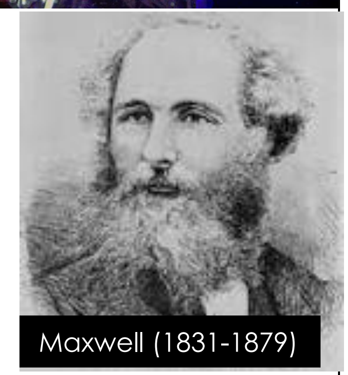
- 1608
  Telescope was invented
- 1610
  Galileo Galilee observed Saturn to be a large body with two smaller bodies beside it



- 1655-59
  Christian Huygens was the first to conjecture that Saturn is not physically connected to its rings. He also discovered Saturn's largest moon, Titan
- 1675
  Jean Dominique Cassini discovered four of Saturn's moons, and a gap ("Cassini Gap") in the Saturn rings
- 1857
  James C. Maxwell proved that the rings are not solid disks but are instead composed of particles

Huygens (1629-1695)

Cassini (1625-1712)

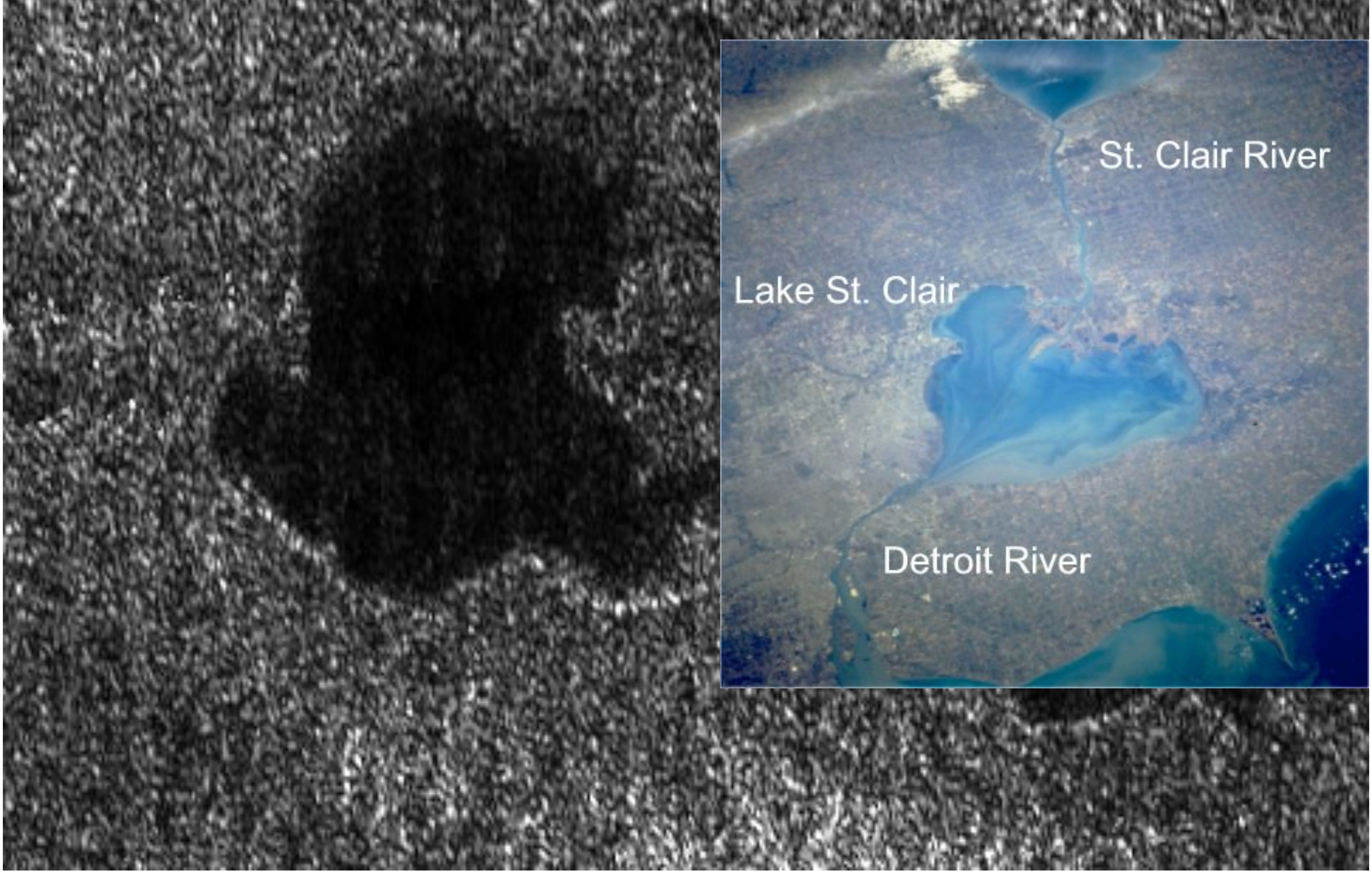


Maxwell (1831-1879)

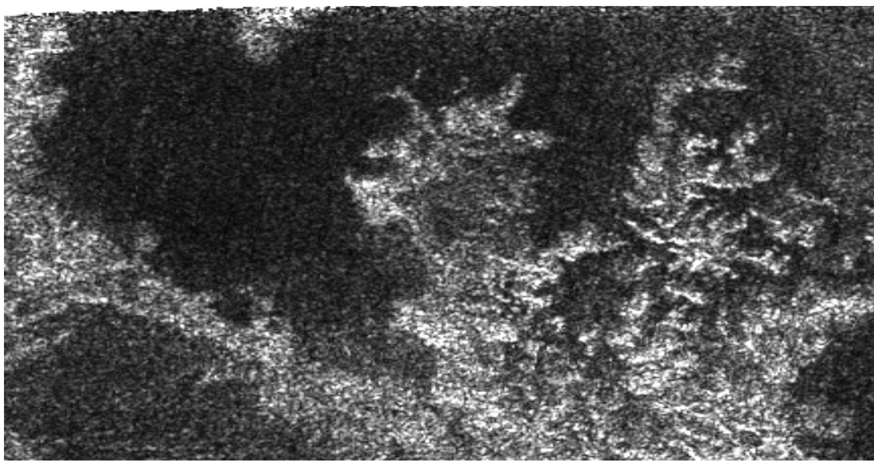
100+ years later

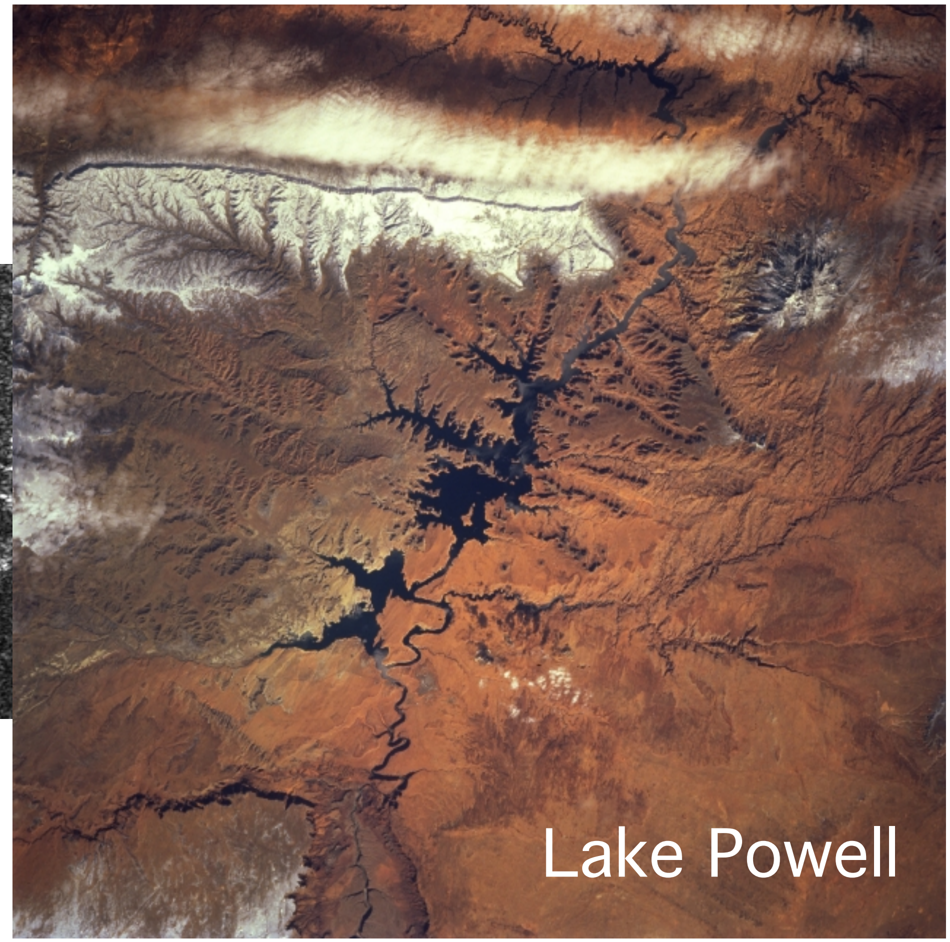
- 1979 NASA Pioneer 11
- 1980-81 NASA Voyager 1 and 2
- 1997 NASA/ESA Cassini

Radar images of Titan "kissing" lakes: Much like lakes on Earth



Radar image of Titan “lakes”





Titan's Atmosphere

- Titan's atmosphere extends **>10** times further into space than Earth's atmosphere
  - Titan's atmosphere extends out to an altitude of 3,000 km
- Composition of the Titan's atmospheres:

Titan's atmosphere	N_2	CH_4	${}_{18}Ar^{40}$ and ${}_{18}Ar^{36}$	H_2	CO
Pre-Cassini [%]	95	3	2	-	-
Today [%]	95–98	1.8–5	0.005	0.1–0.2	0.005

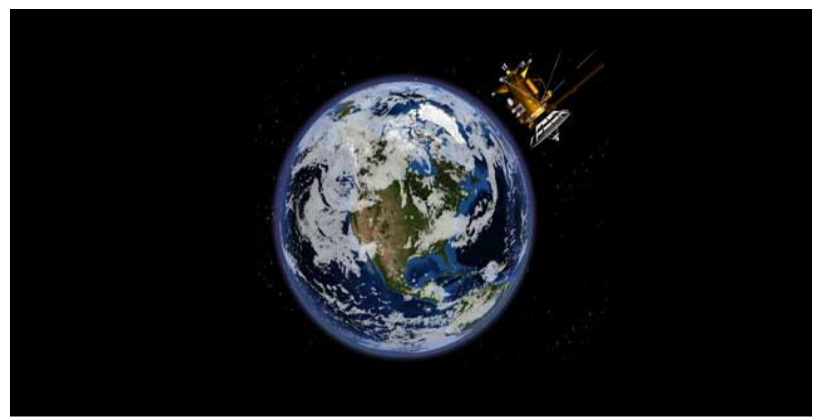
Solar UV light → CH_4 N_2 ← Cosmic particles e^- and protons

Ionization and dissociation

Traces of C_2H_2 , C_2H_4 , C_2H_6 , C_3H_8 , C_3H_4 , C_2N_2 , C_4N_2 , HCN, HC_3N, CH_3CN, and other complex molecules

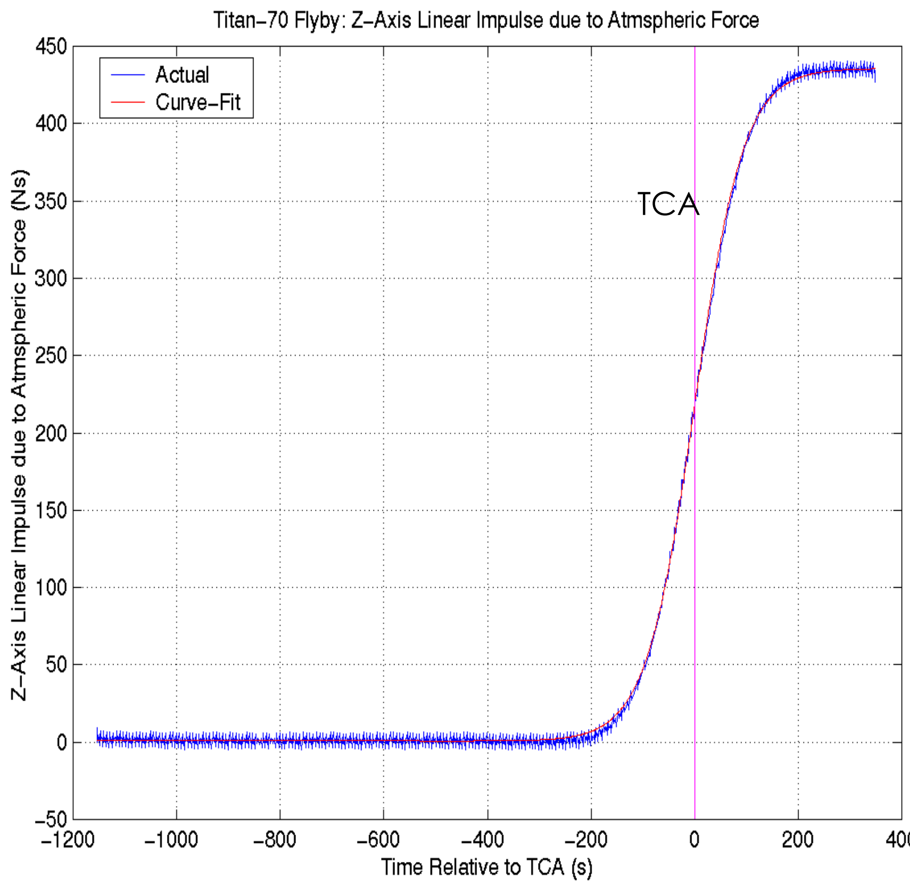
What Motivated Us to Estimate Torque Imparted on S/C? Detection of Leaky Thrusters

- The Cassini spacecraft flew-by the Earth in 1999
  - If a thruster leaks (e.g., stuck open), the expulsing hydrazine will impart angular momentum on the S/C. In response, appropriate thrusters will be fired to maintain the commanded attitude:
    - The draining of hydrazine cannot be allowed to persist indefinitely
    - The trajectory of the S/C will be altered
- A requirement in the Cassini Project Policy and Requirement document:
  - Section 4.2.9.6 *Earth Swing-by Requirements*
    - "Spacecraft fault protection shall be designed to detect and correct thruster level leakage that would otherwise generate a spacecraft translational velocity increment of ≥0.5 m/s for any ..."
- In response, Cassini AACS flight software has a capability to estimate external torque imparted on the S/C
  - The external torque could come from the leaky thruster
  - Or it might come from the Titan atmospheric drag during a Titan flyby



Use of Accelerometer Data to Estimate Atmospheric Force†

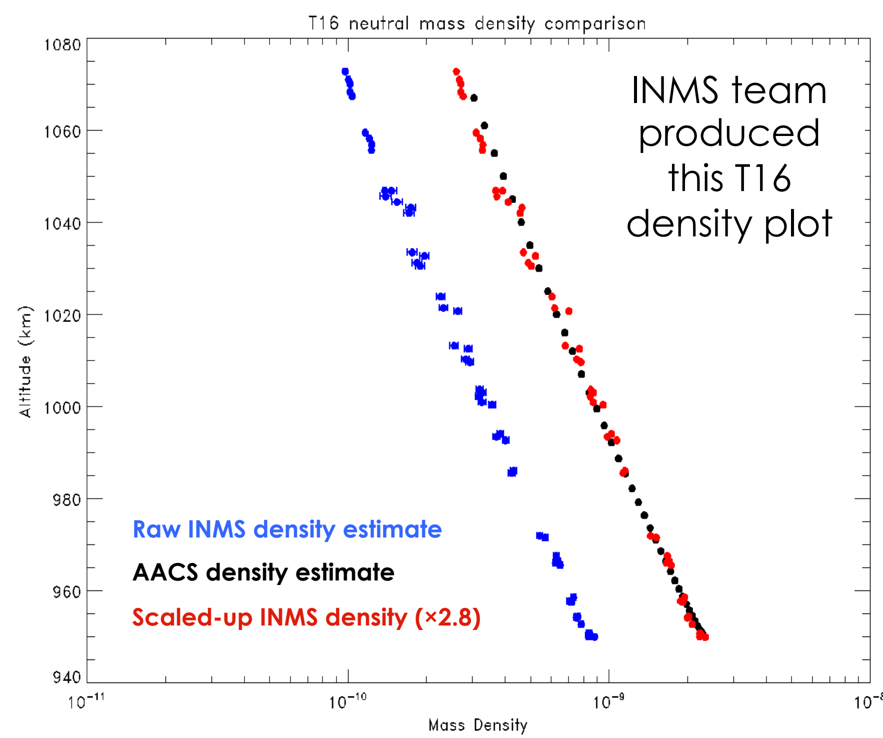
- For two Titan flybys (e.g., T-70 and T-87), the Cassini accelerometer (ACC) was powered on during the flyby. The time history of the ACC count (data number) was used to estimate the Z-axis force imparted on the S/C by the atmospheric density
  - Cassini's ACC is a single-axis sensor that is aligned with the S/C's Z-axis
  - Flight calibrated ACC bias and scale factors were used to process the data number
  - The angle between the RAM vector and the S/C's Z-axis was estimated using Nav's state vector and AACS J2000 attitude
  - Thrusters' firings that imparted a force in the Z-axis direction were accounted for
  - Atm. density at TCA (878-km) estimated by AACS was 4.0e-9 kg/m^3
    - Doppler-based Navigation estimate was 4.02e-9 kg/m^3



†Similar methodologies had been used to estimate atmospheric densities of Venus, Jupiter, and Mars.

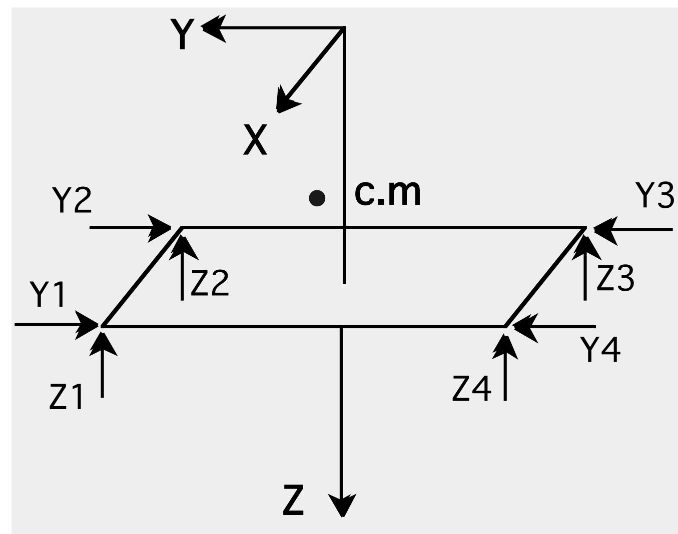
Ion and Neutral Mass Spectrometer (INMS)

- One key scientific objective of INMS is to measure ion and neutral species composition and structure in the upper atmosphere of Titan
- Both INMS and AACS teams made estimates of the Titan atm. density:
    - There are significant differences between the INMS and AACS density estimates
    - The INMS team suspected that their density estimates might be "corrupted" by some electronics-related mistakes made pre-launch
    - One way to remedy this problem is to scale up the INMS density estimate by a factor "f" in order to match its AACS density counterpart
- Work on calibrating INMS density estimates using their AACS counterparts is in progress
- Like AACS and CIRS data, the raw INMS density estimates also exhibit a significant temporal variation



Attitude Control Systems

- Reaction Control System (Thrusters):
  - Eight A-branch thrusters (prime at launch) and eight B-branch thrusters
  - Blow-down (1.1 N at launch)
  - Control system: Bang-Off-Bang (BOB), BW ≈ 0.15 Hz
  - Functions:
    - Low-altitude Titan flybys
    - Small trajectory correction burns (ΔV)
    - RWA Biasing
    - Detumble S/C, others
- Key events:
  - MTA recharge (May 2006)
    - Ahead of multiple Titan flybys with altitude ≈ 950 km
  - Swap prime-ness (March 2009)
    - Two A-branch thrusters had degraded

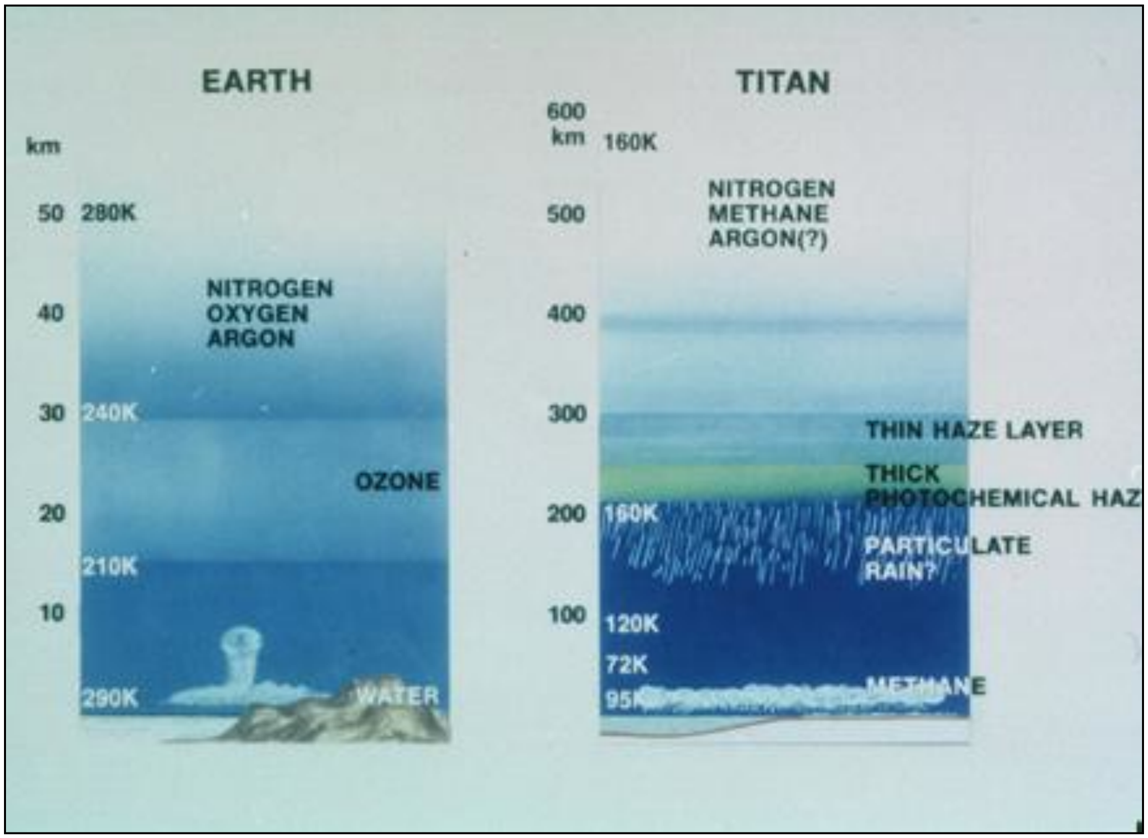


S/C Safety during Low-altitude Titan Flybys

- During a low-altitude Titan flyby, thrusters are used:
  - To overcome Titan atmospheric torque
  - To overcome Titan gravity gradient torque
  - To perform target motion compensation slew
  - To slew the S/C about X, Y, Z-axis (or multi-axis) for Science
  - To maintain a set of commanded per-axis attitude controller dead-band
  - To fight gyroscopic torque (if reaction wheels are on with significant rates)
- The question of whether the S/C has adequate control authority (about all axes) was the focus of the RATAR (Rings and Titan Atmosphere Risk) team in 1990. The answer is highly scenario dependent. Important factors to consider:
  - Titan flyby altitude
  - S/C's (time varying) attitude while it is "inside" the Titan atmosphere
    - Projected area and center of pressure
  - Science slew profile (if any)
  - S/C's inertia properties (c.m. location, etc.)
  - Thruster magnitude
- A set of safe Titan flyby altitudes has been selected in late 2005 by SCO, MP, and TAMWG engineers

Earth's and Titan's Atmosphere

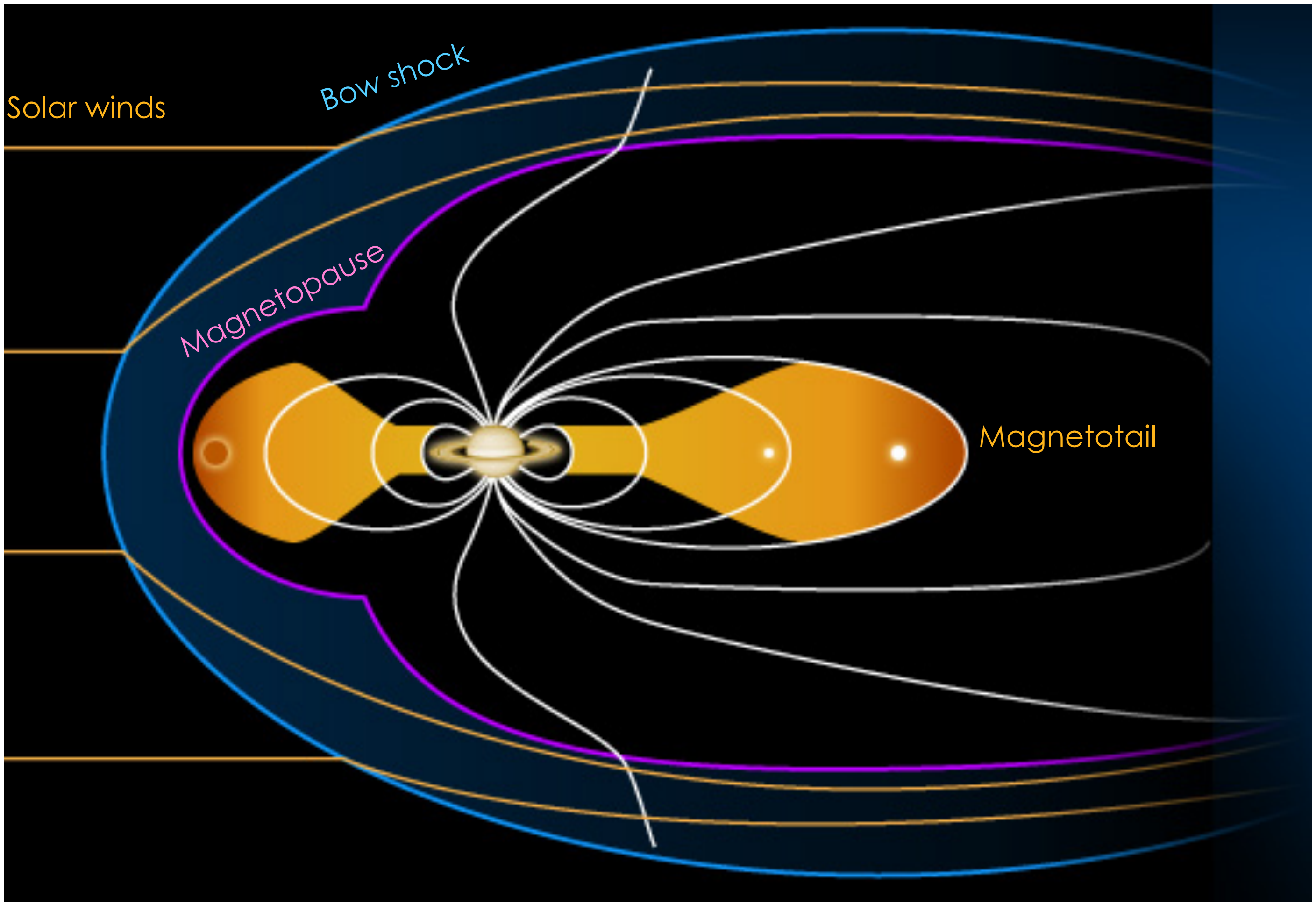
- (Pre-Cassini) Approximate composition of the Titan's atmospheres:
  - N_2: 95%
  - CH_4, H_2, C_2H_2, C_2H_4, C_2H_6, C_3H_4, and others: 3%
  - $_{18}Ar^{40}$ and $_{18}Ar^{36}$ ($_{18}Ar^{38}$?): 2%†
- Titan's atmosphere extends **>10** times further into space than Earth's atmosphere
  - Titan's atmosphere: To 3,000 km



†Earth's atmosphere has 0.93% $_{18}Ar^{40}$ and Mars's atmosphere has 1.6% $_{18}Ar^{40}$

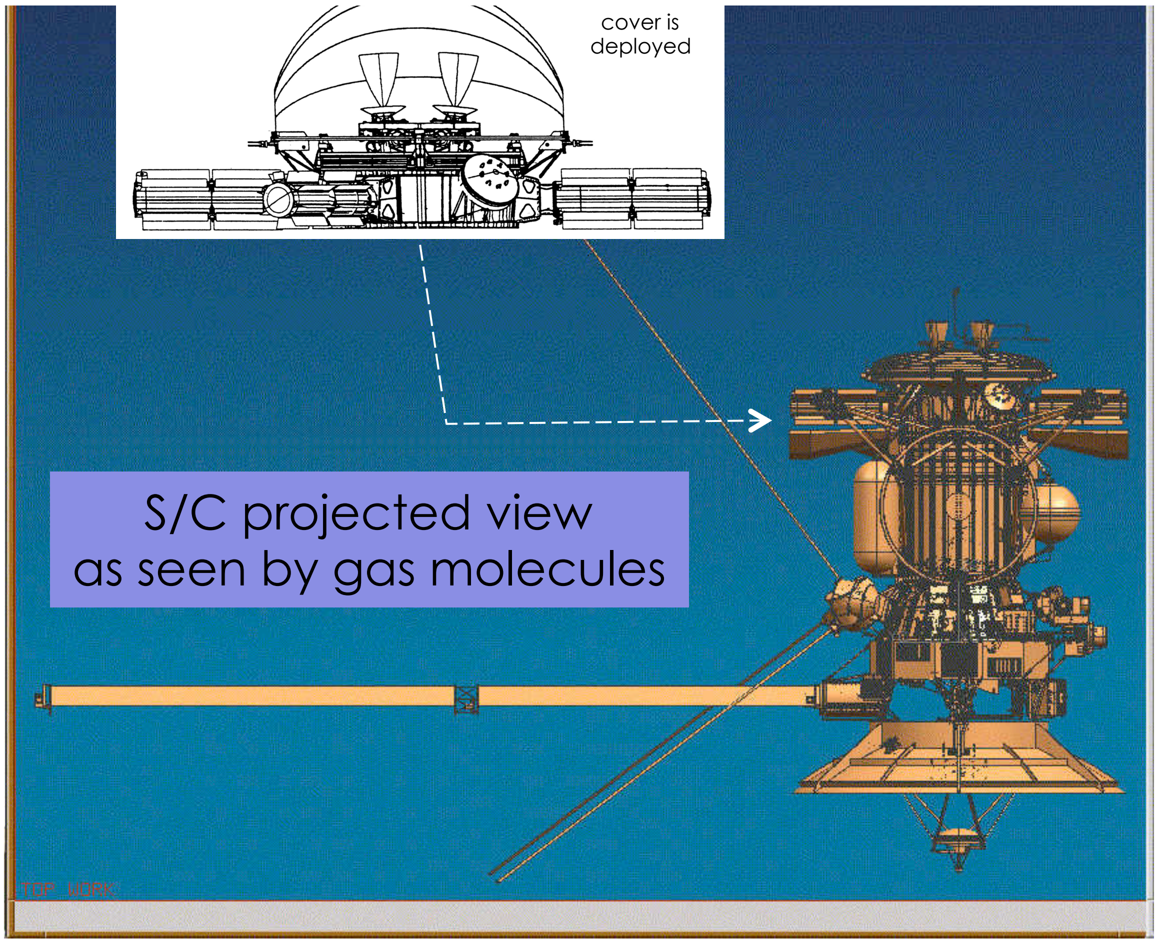
Impacts of the Saturn Magnetosphere on Titan Atm. Density?

- Titan is Inside or outside the magnetosphere at the time of the flyby?



Estimation of Projected Area and C.P. Location

- A total of 144 (12×12) projected views of the S/C were used to estimate the projected area and center of pressure location (by Ground software) as functions of the [Azimuth, Elevation] angles of the RAM velocity vector
  - [Azimuth, Elevation] angles @ 15˚ interval
  - Without the probe and with a stowed main engine cover. MLI is considered



Drag Coefficient in Free Molecular Flow

- During a Titan flyby, the Spacecraft is in a "free molecular flow" field:
  - Molecular speed ratio (S)
  - Diffuse reflection coefficient (σ) ≈1
  - Thermal accommodation coefficient (α) ≈ 1
  - Diffuse drag coefficient estimates (C_D):†
    - Cylinder:

$$C_D = \frac{\sqrt{\pi}}{S} e^{(-\frac{S^2}{2})} \{(S^2 + \frac{3}{2}) I_0(\frac{S^2}{2}) + (S^2 + \frac{1}{2}) I_1(\frac{S^2}{2})\} + \frac{\pi^{\frac{3}{2}}}{4S} \sqrt{\frac{T_{MLI}}{T_\infty}} \approx 2.07$$

    - Sphere:

$$C_D = \frac{2}{\sqrt{\pi}\, S} e^{(-\frac{S^2}{2})} (1 + \frac{1}{2S^2}) + 2(1 + \frac{1}{S^2} - \frac{1}{4S^4}) \mathrm{erf}(S) + \frac{2\sqrt{\pi}}{3S} \sqrt{\frac{T_{MLI}}{T_\infty}} \approx 2.06$$

Representative values:

V	= Spacecraft's velocity ≈ 6.06 km/sec
I_0 (•)	= Bessel function of the first kind, order = 0
I_1 (•)	= Bessel function of the first kind, order = 1
erf(•)	= Error function
T_∞	= Titan atmosphere temperature
T_{MLI}	= S/C MLI skin temperature

- Drag coefficient as estimated by NASA Langley team = 2.02 (for the T-70 flyby)

†Stalder, J.R., Goodwin, G., and Creager, M.O., *A Comparison Between Theory and Experiment for High Speed Free Molecular Flow*, National Advisory Committee for Aeronautics, NACA Technical Note 2244,1950.

Stalder, J.R. and Zurick, V.J., *Theoretical Aerodynamic Characteristics of Bodies in a Free Molecular Flow Field*, NACA Technical Note 2423, July 1951.

Diffuse Drag Coefficient of Cylinder: Experimental Data†

- Gas used: Nitrogen
- Mach number ≈ 10.1

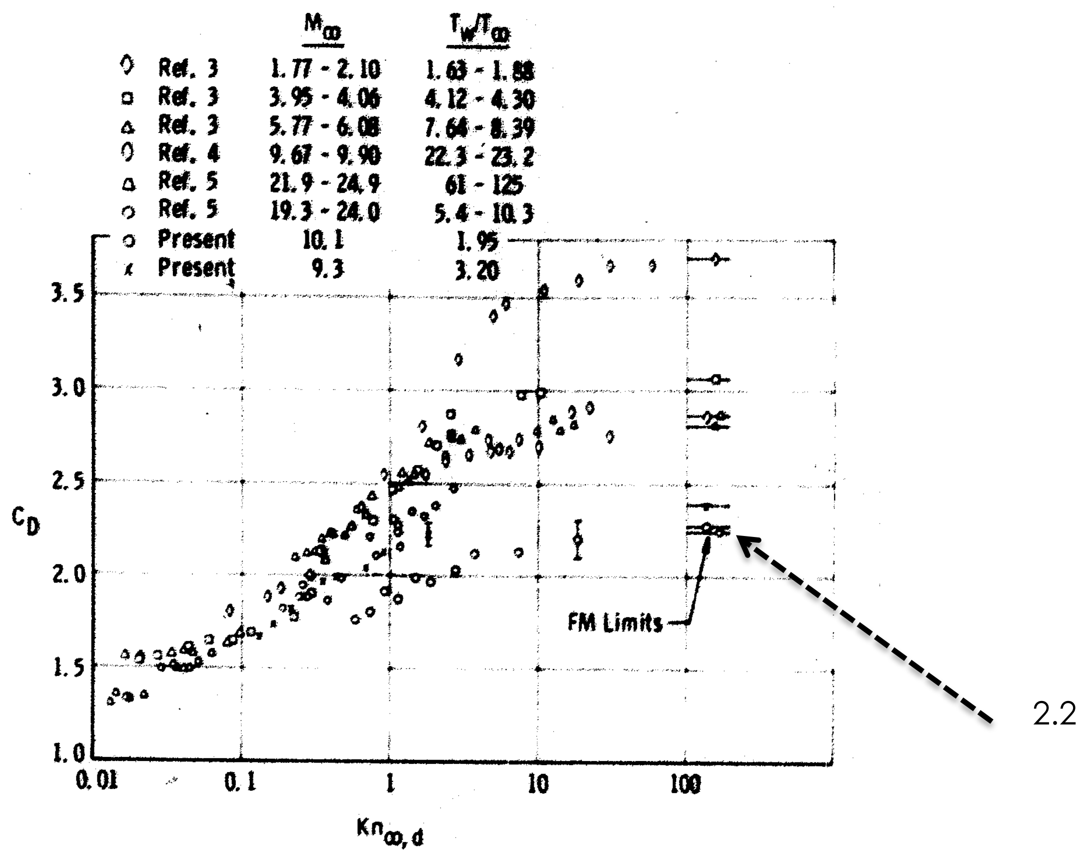


Fig. 2 Transitional cylinder drag coefficient

†Sharpe, C.L., *Experimental Cylinder Drag Data for Hypersonic, Rarefied Flow*, AIAA Journal, Vol. 7, No.8, August 1969.

Titan Gravity Gradient (GG) Torque

- Titan gravity gradient torque is a function of both the distance between the c.m. of the S/C and Titan, and the S/C's attitude relative to the S/C-to-Titan vector
- With the worst-case S/C's orientation, and when the S/C is at TCA, the G.G. torque is:

$$T_{GG\text{-}MAX} = \frac{3}{2}\mu_{Titan}\frac{(I_{max} - I_{min})}{d^3}$$

where:

μ_{Titan} = $GM_{Titan} \approx 8978.2$ km³/sec²

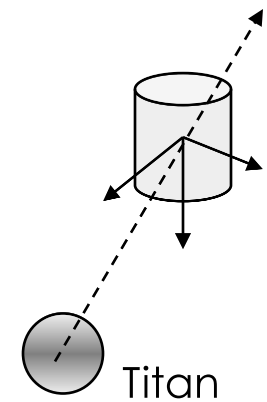
d = distance between Titan's c.m. and S/C's c.m.

= 950+2575 km (at closest approach, 950 km)

I_{max} = $I_{XX} \approx 7200$ kg-m² (representative)

I_{min} = $I_{ZZ} \approx 3700$ kg-m² (representative)

$T_{GG\text{-}MAX}$ ≈ 0.001076 Nm



≈ about two orders of magnitude smaller than the Titan atmospheric torque imparted on S/C during a 950-km flyby

Magnetic, Solar Radiation, and RTG Torque

- Magnetic disturbance torque results from the interaction between the S/C's residual magnetic field and the magnetic field of Saturn

$$T_{magnetic} = M_{Moment\text{-}arm} \times \frac{B_{Saturn}}{R_{ps}^{3}}$$

where:

$M_{Moment\text{-}arm}$ = S/C magnetic moment arm = 1.4 Amp-m^2

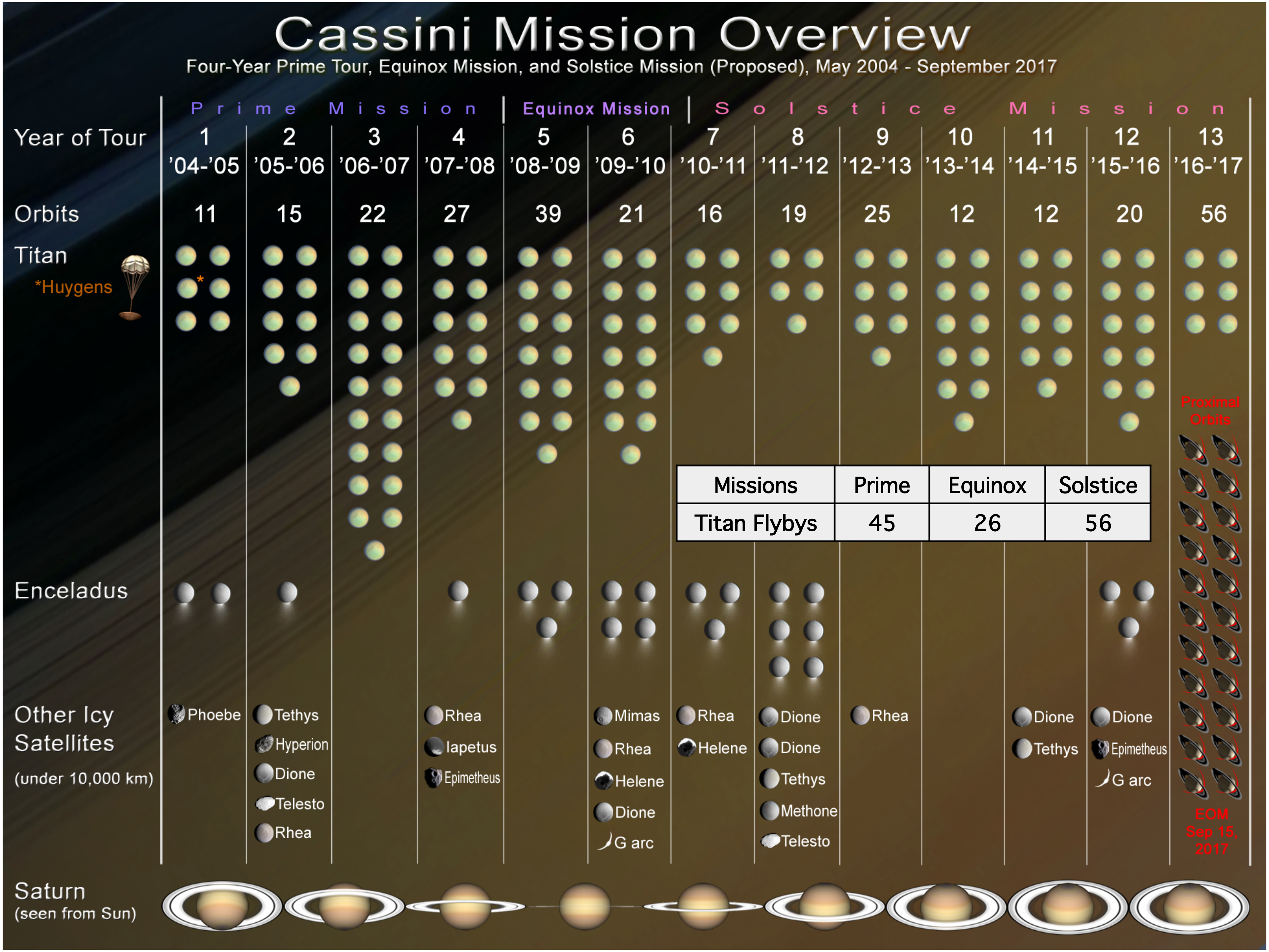
B_{Saturn} = Magnetic flux density on the surface of Saturn = 8.3e-5 kg-s^{-2}-Amp^{-1}

R_{ps} = distance between Saturn and S/C in planet radii = 20.3 (at Titan)

$T_{Magnetic}$ ≈ 1.38e-8 Nm

- Solar radiation torque and RTG torque ≈ 2e-6 Nm
- Combined magnetic, solar radiation, and RTG torque ≈ 2.1e-6 Nm
  - About five orders of magnitude smaller than the Titan atmospheric torque imparted on S/C during a 950-km TCA altitude flyby

Conclusion: We can safely ignore these small environmental torques


Cassini Mission Overview
Four-Year Prime Tour, Equinox Mission, and Solstice Mission (Proposed), May 2004 - September 2017
Prime Mission
Equinox Mission
Solstice Mission
Year of Tour
1 '04-'05
2 '05-'06
3 '06-'07
4 '07-'08
5 '08-'09
6 '09-'10
7 '10-'11
8 '11-'12
9 '12-'13
10 '13-'14
11 '14-'15
12 '15-'16
13 '16-'17
Orbits
11
15
22
27
39
21
16
19
25
12
12
20
56
Titan
*Huygens
*
Proximal Orbits
Missions | Prime | Equinox | Solstice
Titan Flybys | 45 | 26 | 56
Enceladus
Other Icy Satellites
(under 10,000 km)
Phoebe
Tethys
Hyperion
Dione
Telesto
Rhea
Rhea
Iapetus
Epimetheus
Mimas
Rhea
Helene
Dione
G arc
Rhea
Helene
Dione
Dione
Tethys
Methone
Telesto
Rhea
Dione
Tethys
Dione
Epimetheus
G arc
EOM Sep 15, 2017
Saturn
(seen from Sun)